Energy-saving Effect of Thermal Energy Storage Using Introduced Outdoor Air

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Abstract

Recently, buildings with thermal energy storage system have increased because of its economic advantage. In thermal energy storage system using introduced outdoor air, building masses are used as thermal storage media and cooled by outdoor air introduced by a mechanical fan in night-time. In spring and autumn, the cooled building masses can work to reduce cooling load in day-time. In this study, the stored heat was calculated by using simple heat transfer models for various building masses, and the energy performance of this system was evaluated quantitatively by system simulation. It was found that the optimized flow rate of outdoor air can be obtained by comparing the electric power consumption by a mechanical fan with the reduced cooling load because the mechanical fan is the only device requires electric power in night-time.

KEY WORDS: Simulation, Outdoor air, Thermal energy storage

Introduction

Thermal energy storage system has become popular in Japan because of lower electricity charge at nighttime. Thermal energy storage system using floor slabs, beam structures and office furniture (building masses) as storage media can reduce the initial cost and the installation space in comparison with water or ice storage system having large tanks. Furthermore, the thermal energy storage system using outdoor air can save energy because cool outdoor air in nighttime is introduced to cool building masses.

This paper presents the heat transfer models of each building mass and introduces an actual thermal energy storage system using outdoor air. In this system, building masses are cooled by outdoor air during nighttime and cool the return air from office room during daytime. The cooled building masses can reduce cooling load. However, it is difficult to evaluate the actual performance of thermal energy storage system having various building masses because the heat transfer between the building masses and introduced outdoor air is very complicated. In this paper, the building heat transfer simulation incorporating each heat transfer model was conducted, and it was found that the optimum outdoor air rate introduced by mechanical fan can be obtained by this simulation.

Heat Transfer Models

The concrete floor slab has the largest heat capacity in various building masses, and temperature of return air from the room is affected by time lag of temperature in concrete slab. Therefore, the heat capacity of concrete slab has been considered in system simulation to evaluate the effect of stored heat in concrete slab. In case that heat capacity of building masses excluding concrete slab is considered in simulation, temperature of these building masses has been simply regarded as uniform and equal to the room air temperature, and time lag of temperature in building masses has been ignored. In this study, however, heat capacity of building masses such as beam structures and office furniture is assumed to contribute the heat transfer between the building masses and introduced outdoor air, and simple heat transfer models which can evaluate heat flux at surface of building masses accurately are suggested.

In simulating heat transfer for the building masses relatively thin, the surface heat flux can be assumed as one-dimensional. Here, the concrete slab was regarded as thin building mass. The temperature in the slab can be calculated by the following unsteady heat conduction equation,

$$\rho c_p \frac{\partial \theta(x,t)}{\partial t} = \lambda \frac{\partial^2 \theta(x,t)}{\partial x^2} \qquad \text{(Eq. 1)}$$

The heat flux on concrete slab surface can be written as follows:

$$q_1 = h\left(\theta(0,t) - \theta_r\right) \qquad \text{(Eq. 2)}$$

The heat capacity of other building masses is not as large as that of concrete slab. If the temperature distribution in all building masses is calculated by using Eq.1, the building heat transfer simulation becomes complex and time-consuming. Therefore, simple heat transfer models are applied to the building masses (furniture and beam structures) excluding concrete slab and the heat through surface of building masses can be calculated easily. Here, the desk board is analyzed as building furniture. Heat transfer model of desk board is based on the assumption that temperature distribution in desk board is assumed to be quadratic, and this model is called the quadratic model.

The quadratic temperature distribution of building mass can be written as follows:

$$\theta(x,t)=\alpha(t)x^2+\beta(t)x+\gamma(t) \quad \text{(Eq. 3)}$$

$\alpha(t),\beta(t),\gamma(t)$ are unknown coefficients of quadratic function. At the surface of desk board (*x=0*), the boundary condition is as follows:

$$\lambda\frac{\partial\theta(x,t)}{\partial x}=h\left(\theta(0,t)-\theta_r\right) \quad \text{(Eq. 4)}$$

As the boundary condition at the center of desk board (*x*=*l*) perfect insulation was applied and written as

$$\lambda\frac{\partial\theta(l,t)}{\partial x}=0 \quad \text{(Eq. 5)}$$

The time integration of heat flux through surface is equal to the stored heat in desk board from surface to center of desk board at time t, and the heat balance equation for the board can be written as follows:

$$\int_0^t h\left(\theta(0,t)-\theta_r\right)Adt=-\int_0^l\frac{\lambda}{a}\left(\theta(x,t)-\theta(x,t)\right)Adx \quad \text{(Eq. 6)}$$

From these equations, (Eq.4) - (Eq.6), $a(t),b(t),c(t)$ can be represented the functions of mean temperature in desk board, $\bar{\theta}(t)$. The change rate of $\bar{\theta}(t)$ and the heat flux exchanged at the surface of desk board can be expressed respectively as follows:

$$\frac{\partial\bar{\theta}(t)}{\partial t}=\frac{3ha}{l(hl+3\lambda l)}\left(\theta_r-\bar{\theta}(t)\right) \quad \text{(Eq. 9)}$$

$$q_2=\frac{3h\lambda}{hl+3\lambda l}\left(\bar{\theta}(t)-\theta_r\right) \quad \text{(Eq. 10)}$$

Two models, an unsteady conduction equation model and a quadratic model, are compared under the conditions of **Table1** in order to verify the accuracy of quadratic model. **Fig.1** shows the variation in heat flux calculated by these two models. The difference between the unsteady conduction equation model and the quadratic model are very small in thin furniture. From the result, the quadratic model can be used as heat transfer model of thin furniture instead of the unsteady conduction equation model.

Table1
Condition in heat transfer model of desk board

Variable	Value
θ_r [°C]	18
$\theta(x,0)$ [°C]	28
λ [W/m·K]	0.15
h [W/m²·K]	5.0
ρc_p [kJ/m³·K]	714
l [m]	0.05

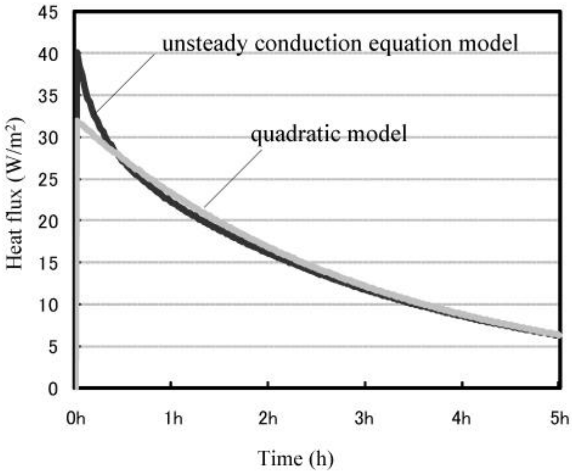


Fig.1 Comparison of heat flux by two models

In the heat transfer model of beam structure, the quadratic model can be used as heat transfer model of fire protection covering beam structure, and mean internal temperature weighted by each heat capacity of steel or fire protection covering material is used. Temperature of beam structure itself is assumed to be uniform because of high heat conductivity of steel. In the heat transfer model of sprinkler piping in ceiling chamber, the internal temperature is assumed to be uniform because of high heat conductivity.

System Simulation

A building heat transfer simulation is conducted in order to calculate energy-saving performance of this system. The outline of a building adopted thermal energy storage system by outdoor air is shown in **Table2** and the typical floor plan is shown in **Fig.2**. In cooling building masses in the ceiling chamber, the mechanical fan in air-handling-unit introduces outdoor air. The outdoor air is supplied to ceiling chamber through the return duct and cools the concrete slab, beam structures and sprinkler piping. Then the air is introduced into the office room through air supply openings which are used as suction port at the time of air-conditioning in daytime, and the introduced air cools the office furniture. Finally, the air is exhausted from natural ventilation openings above windows.

Building use : office, parking, substation, DHC plant
Total floor area : 106,000m^2
Stories : 5 stories in underground and 41 stories on the ground
Air handling units in each floor : two units for ambient (8,200m^3/h), four units for task(6000m^3/h), one unit for EV hall

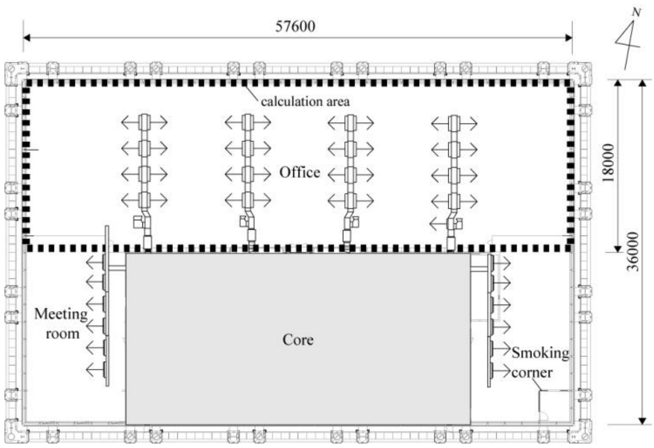


Fig.2 Typical floor plan

The energy saving performance was studied by the building heat transfer simulation surrounded by a dotted line shown in **Fig.2**. From 18:00 to 3:00 (Non-operating period), the outdoor air is not introduced anywhere and the air conditioners are turned off. From 3:00 to 8:00(Storage period), the natural outdoor air is introduced to the ceiling camber by mechanical fan and the openings for natural ventilation are opened. From 8:00 to 18:00(Air-conditioning period), the air conditioners keep the room air temperature at preset temperature.

Fig.3 shows the schematic of heat transfer between the air introduced from outside and the building masses. The room air temperature is assumed to be uniform and constant in air-conditioning period and the supplied outdoor air temperature into ceiling chamber is assumed to be the same as the measured outdoor air temperature from 18:00 May 20th to 18:00 May 21st, 2008 in the storage period (**Fig.4**).

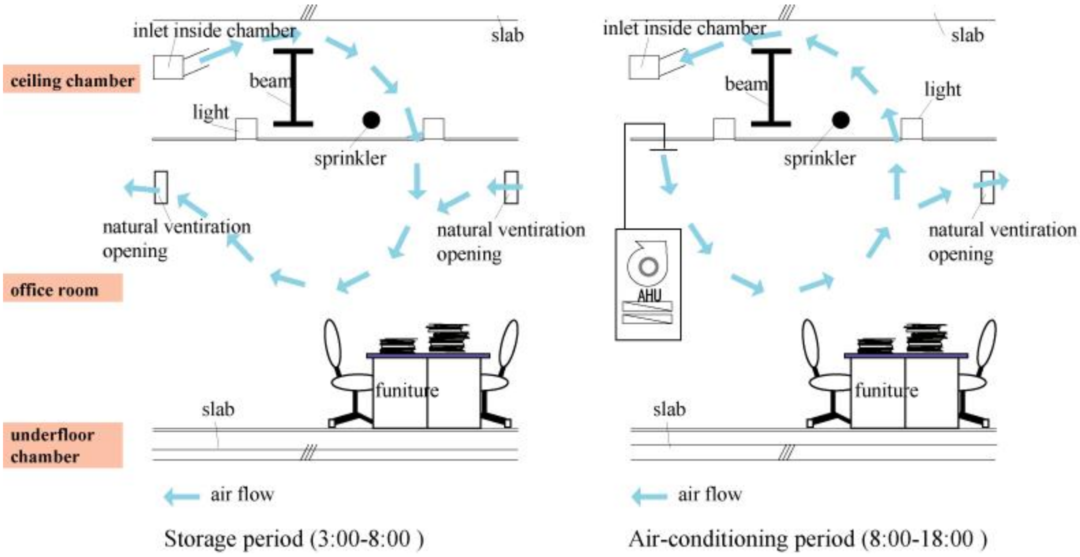


Fig.3 Schematic air flow pattern in heat transfer simulation at storage period and at air-conditioning period

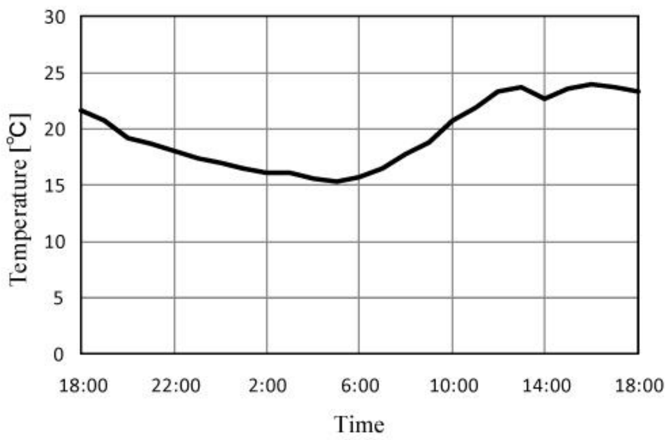
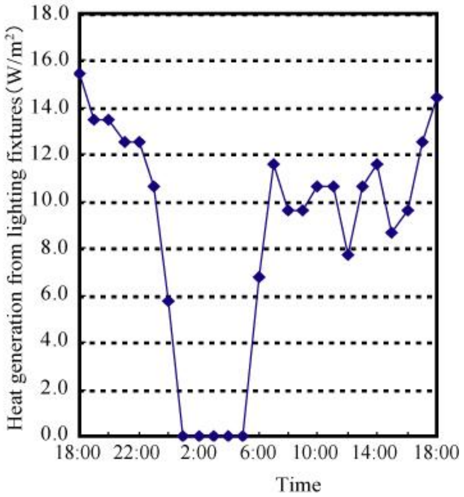


Fig.4 Outdoor air temperature from 18:00 May 20th to 18:00 May 21st, 2008

In this building, the air is supplied into the office room through slits in lighting fixtures. Therefore, the effect of heat generation from lighting fixtures should be considered. The heat generation from lighting fixture was assumed to be equal to measured electric power consumption from 18:00 on May 20th to 18:00 on May 21st in 2008. **Fig.5** shows the heat generation from lighting fixtures calculated from the measured electric power consumption. **Fig.6** shows the distribution of. In this simulation, 20% of heat from lighting fixtures was released into the office room air, and 20% was radiated to the surface of furniture (desk board). The 60% of heat from lighting fixtures is assumed to be heat up the air in ceiling ch



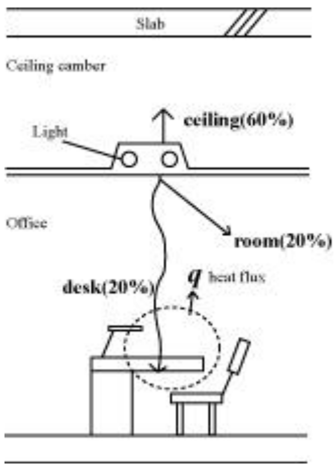


Fig.5 Heat generation from lighting fixtures

Fig.6 Distribution of lighting heat

Performance Evaluation

In evaluating of energy saving performance, the air flow rate introduced from outside by mechanical fan is important factor because the energy was only used by a mechanical fan in the storage period. The electric power required by mechanical fan is also increase if the air flow rate increase. The optimized outdoor air flow rate can be found by comparing electric power consumption for the fan with the energy consumption for the air-conditioning. The released heat in building masses divided by the coefficient of performance (COP) is the energy consumption in the air-conditioning period by the cooled building masses. The value of COP is 2.35 that is the COP of DHC plant that supplies energy to this building. The energy reduction in the air-conditioning period by the cooled building masses is obtained by subtracting the electric power required for the fan from the effect of thermal energy storage. **Table3** shows the condition of this system simulation and **Table4** shows the condition of heat transfer models in this system simulation.

Table3 Calculation conditions in simulation

Case	Value
Room temperature during air-conditioning[^{o}C]	25.5
Supply airflow rate during building thermal storage[m^3/s]	3.8
Airflow rate from natural ventilation openings during building thermal storage[m^3/s]	2.0
Supply airflow rate during air-conditioning[m^3/s]	1.6
Constant internal heat generation in storage period.[W/m^2]	4.0

Table4 Conditions of building elements in heat transfer models in simulation

Element		Heat conductivity[W/mK]	Volumetric specific heat[kJ/m^3K]	Thickness[mm]	Division number
slab		1.0	10000	150	10
furniture		0.15	714	100	-
beam					
	steel	51.5	3713	18	-
	fire protection material	0.095	384	65	-
sprinkler piping(water)		-	4168	-	-

Results and Discussion

Table5 shows the stored heat and energy consumption in the air-conditioning period by the cooled building masses. The data of electric power consumption of a mechanical fan are obtained by Building and Energy Management System (BEMS). The electric power consumption of mechanical fan in the storage period is 21.8 kWh. In **Table5**, “Storage mode” means that the building is both ventilated naturally and introduced outdoor air by the mechanical fan under the condition of **table3**. In storage mode, the building masses cooled by outdoor air can work to reduce cooling load and energy consumption of air conditioning system. However, in non-storage mode, the building masses are warmed by internal heat generation, and the building masses work to increase cooling load. According to **Table5**, the energy reduction in the air-conditioning period by the cooled building masses in Storage mode is 52.2kWh, and the difference of energy consumption of air-conditioner between Non-storage mode and Storage mode is 91.3kWh under the calculation conditions in Table3 and Table4.

Table5 Stored heat and Energy consumption in air-conditioning period

	Stored heat(kWh)		Energy consumption(kWh)	
	Storage mode	Non-storage mode	Storage mode	Non-storage mode
slab	-82.4	59.4	-35.1	25.3
furniture	-49.3	23.0	-21.0	9.8
beam structure	-31.2	9.8	-13.3	4.2
sprinkler piping	-10.8	-0.2	-4.6	-0.1
		fan	21.8	0.0
		total	-52.2	39.2
		deference	91.3	

Optimum operation of this system can be regarded as an operation of using the minimum energy. In this system, the energy reduction is determined by the balance of electric power consumption of mechanical fan. The electric power consumption of mechanical fan is proportional to the third power of air flow rate introduced from outside by mechanical fan , and the air flow rate introduced from outside by mechanical fan that makes the energy reduction in the air-conditioning period by the cooled building masses maximum can be obtained. **Fig.7** shows the relationship between the saved electric power and the air flow rate introduced from outside by mechanical fan. When the value of air flow rate is 0 m^3/s, the building is only ventilated naturally at storage period. According to **Fig.7,** the energy reduction per day by the cooled building masses reaches maximum value when the air flow rate introduced from outside by mechanical fan is about 3 m^3/s.

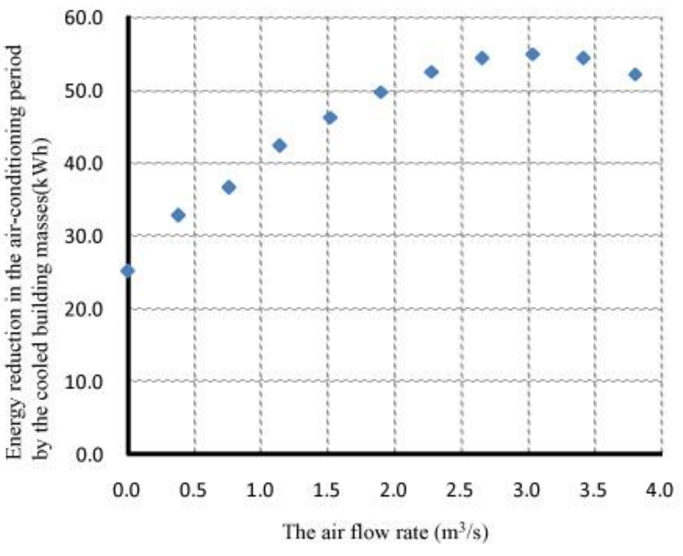


Fig.7 Relationship between the energy reduction per day by the cooled building masses and the air flow rate introduced from outside

Conclusions

In this paper, a simple heat transfer model of building masses, in which temperature distribution is assumed to be quadratic, is presented. By using this model, the surface heat flux of building masses can be obtained easily. In this thermal energy storage system simulation, the quadratic model can be used to calculate the surface heat flux of building masses such as desk board. The unsteady conduction equation model can be used to calculate the surface heat flux of concrete slab because of its large heat capacity. According to this system simulation, the thermal energy storage system using introduced outdoor air has the potential to increase the energy reduction in the air-conditioning period by the cooled building masses

Nomenclature		
θ_r	preset room temperature	[^{o}C]
$\theta(x,t)$	building mass temperature	[^{o}C]
$\bar{\theta}(t)$	mean building mass temperature	[^{o}C]
x	distance from the surface of a building mass	[m]
λ	building mass heat conductivity	[W/m·K]
h	heat-transfer coefficient	[W/m^2·K]
ρ	density of building mass	[kg/m^3]
c_p	specific heat under constant pressure	[J/kg·K]
l	thickness of building mass×1/2	[m]
A	calculation area of the building	[m^2]
A_f	area of office space	[m^2]
q_1	heat flux of unsteady conduction equation model	[W/m^2]
q_2	heat flux of quadratic model	[W/m^2]
q_l	heat load from lighting fixture	[W/m^2]
W_l	he electric power consumption for lighting	[W]
W_a	energy reduction in the air-conditioning period by the cooled building masses	[kWh]
Q_a	Cooling heat load from building masses	[kWh]

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